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In accordance with the referenced agreement, the Ship Design Tools Project Final Project Report and Form SF 298 is attached. If you have any questions, please don't hesitate to contact me at (843) 760-4364 or carpentier@aticorp.org.

Attachment

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14. ABSTRACT

This research focused on developing design tools that will apply to the innovative ship concepts envisioned for the next generation of Navy surface ships. Today's naval vessels are supported almost entirely by hydrostatics; high-speed boats, on the other hand, are supported almost entirely by dynamic lift in planing. The medium-size, high-speed ships of current and future interest to the Navy fall in the middle ground where both hydrostatics and planing dynamics play significant roles in ship performance and must be included in any rational design methodology. The proposed research will develop two of the components of the tool-set needed for design of semi-planing/semi-displacement ship design, specifically: (1) adaptation of planing theory for including dynamics in calm water ship performance, and (2) adaptation of impact theory for predicting wet-deck slamming of catamarans.

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REPORT INTRODUCTION

ABSTRACT:

This research focused on developing design tools that will apply to the innovative ship concepts envisioned for the next generation of Navy surface ships. Today's naval vessels are supported almost entirely by hydrostatics; high-speed boats, on the other hand, are supported almost entirely by dynamic lift in planing. The medium-size, high-speed ships of current and future interest to the Navy fall in the middle ground where both hydrostatics and planing dynamics play significant roles in ship performance and must be included in any rational design methodology. The proposed research will develop two of the components of the tool-set needed for design of semi-planing/semi-displacement ship design, specifically: (1) adaptation of planing theory for including dynamics in calm water ship performance, and (2) adaptation of impact theory for predicting wet-deck slamming of catamarans.

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Contents

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FOREWARD

This research focused on developing design tools that will apply to the innovative ship concepts envisioned for the next generation of Navy surface ships. Today's naval vessels are supported almost entirely by hydrostatics; high-speed boats, on the other hand, are supported almost entirely by dynamic lift in planing. The medium-size, high-speed ships of current and future interest to the Navy fall in the middle ground where both hydrostatics and planing dynamics should play significant roles in ship performance and must be included in any rational design methodology. The proposed research will develop two of the components of the tool-set needed for design of semi-planing/semi-displacement ships, specifically: (1) daptation of planing theory for including dynamics in calm water ship performance, (2) adaptation of impact theory for predicting wet-deck slamming of catamarans

PREFACE (announces purpose and scope; acknowledge contributions of non-authors)

The first task of this project focused on extension of planing theory and computation to semi-planing at non-infinite Froude number. The objective of the work for to find a method for predicting the calm-water resistance of the semi-displacement/semi-planing ship type, as well as the limiting cases of full displacement and full planing vessels.

The second task of this project focused on an impact model for predicting catamaran wet-deck slamming pressure loads and structural interaction. Two codes for catamaran wet-deck impact analysis, with structural interaction, were developed.

The analysis details of the research are given in the three annual reports identified in the references as the Task 1 and Task 2 Annual Reports.

The following UNO - NAME students received MS degrees for their contributions to the outcome of the work: Ahmed Ibrahim and Mark VanZandt.

REPORT BODY

SUMMARY (summarize problem, results, conclusions, recommendations)

Task 1: Extension of planing theory and computation to semi-planing at non-infinite Froude number.

Objective: Method for predicting the calm-water resistance of the semi-displacement/semi-planing ship type, as well as the limiting cases of full displacement and full planing vessels.

A code for prediction of calm water planing had been assembled from the infinite Froude number theory of (Vorus, 1996), with a correction from the flat ship planing theory of (Mauro, 1967) to allow for wave generation at non-infinite Froude number; this allowed for dynamic lift development. This code was then coupled to the usual non-lifting displacement hull code with a Michell's Integral (Michell, 1898) wave resistance routine.

The resulting computations with the combined code showed a substantial reduction in net resistance (viscous, wave, and induced) compared to the purely displacement hull analysis, which included viscous and non-lifting wave resistance components. The complete analysis is presented in reference 1.

Task 2: Impact model for predicting catamaran wet-deck slamming pressure loads and structural interaction.

Objective: Development of codes for catamaran wet-deck impact analysis, with structural interaction.

The year 2 analysis was for the typical catamaran with flat wet deck. The flat wet deck, which is bounded by the demi-hulls laterally, forces the impact flow to be fore-and-aft, and therefore approximately 2-dimensional in the vertical fore-and-aft plane. This provides the modeling simplification of 2-D unsteady foil theory (Newman, 1976) for the impacting wet-deck. This code was constructed with input being the vertical impact velocity constructed from heave and pitch components of the ship motion relative to the wave contour.

The 2nd code developed for the impact work in year 2 was for generating the relative impact velocity. After some study it was clear that the maximum occurred in long head waves, with the wave exciting frequency being higher than the heave/pitch natural frequency i.e., running supercritical inn the waves.

Calculation were performed for approximate catamaran and wave characteristics. The analysis indicated , with flat wet deck, that very high levels of impact were unavoidable, even with some level of hull flexibility allowed for. This analysis is presented in reference 2

This conclusion on the undesirability of flat wet decks implied the need for investigating non-flat wet decks, which led to the 3rd year of the project. The characteristic non –flat wet-deck is exhibited in the Incat-style wave-piercing bow with center-hull, which is convex down as with a monohull. However, analysis here focused on a concave wet decks and showed that manageable impact loads, relative to the flat and convex wet deck cases, were very achievable. The supporting analysis is reference 3.

INTRODUCTION (state subject, purpose, scope and plan for developing report)

Subject: The general **subject** of this research is high-speed ships. The **purpose** is to develop better predictive tools for understanding and reliably designing high-speed ships. The **scope** is limited to two of the most important aspects of high-speed ship performance where the physical understanding is insufficient and the design tools are inadequate: 1) semi-planing in calm water and, 2) multi-hull wet-deck slamming in waves. The **plan** for the report is to show and explain the most important tables and graphs developed from the analysis which lead to the stated conclusions. (The mathematical details of the analyses are outlined in the annual reports sent to ONR at the ends of each of the three years.)

METHODS, ASSUMPTIONS, AND PROCEDURES (describe research methodology)

1. Calm-water semi-planing (year 1)

A code for prediction of calm water planing had been assembled from the infinite Froude number theory of (Vorus, 1996), with a correction from the flat ship planing theory of (Mauro, 1967) to allow for wave generation at non-infinite Froude number; this allowed for dynamic lift development. This code was then coupled to the usual non-lifting displacement hull code with a modified Michell's Integral (Michell, 1898) wave resistance routine.

2. Catamaran wet-deck slamming (years 2 and 3)

The year 2 analysis was for the typical catamaran with flat wet deck. The flat wet deck, which is bounded by the demi-hulls laterally, forces the impact flow to be fore-and-aft, and therefore approximately 2-dimensional in the vertical fore-and-aft plane. This provides the modeling simplification of 2-D unsteady foil theory (Newman, 1976) for the impacting wet-deck. This code was constructed with input being the vertical impact velocity constructed from heave and pitch components of the ship motion relative to the wave contour.

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RESULTS AND DISCUSSION (present findings and discuss significance)

1. Calm-water Semi-planing (year 1)

Figure 1 shows the running wetted body plan of the prototype evaluation case constructed and called the "Hybrid SemiHull;" Figure 2 is the running half-breadth, and Figure 3 is the variation of deadrise angle over the 60m length,. The speed of 50 knots, corresponding to a Froude number, Fn = 1.064, and the displacement is 1565 tons.

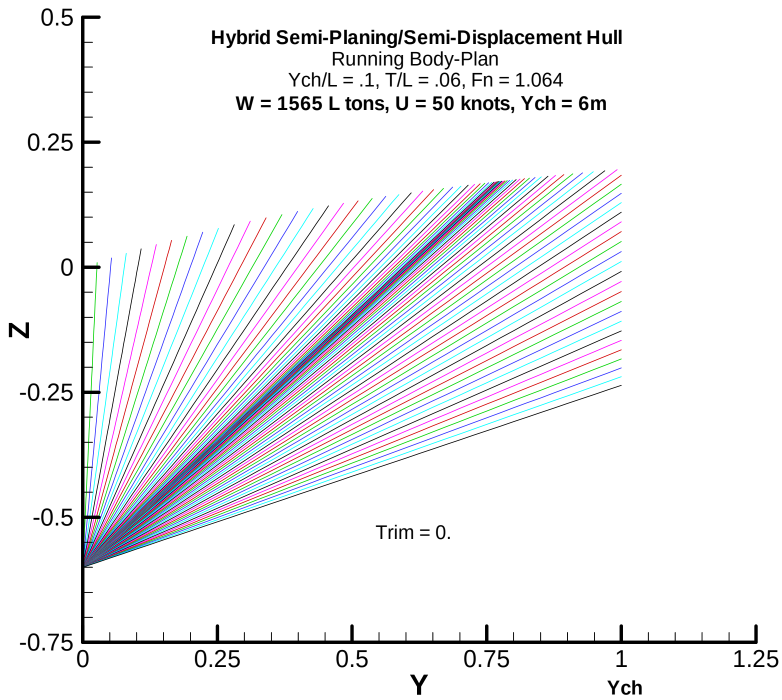

Fig 1 : Running Body-Plan of Hybrid Semihull

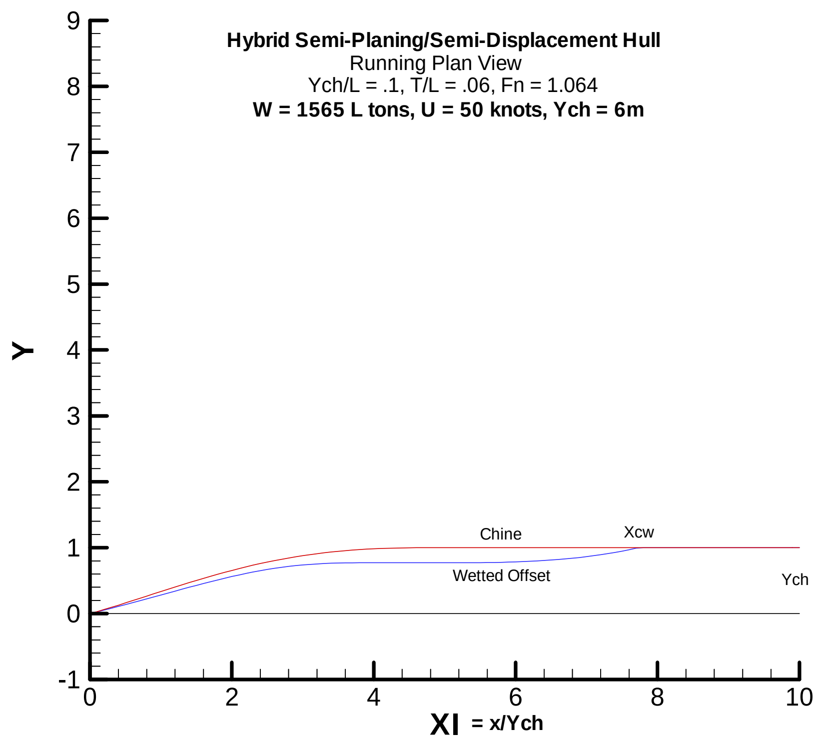

Fig 2 : Running Half-Breadth Plan of Hybrid Semihull

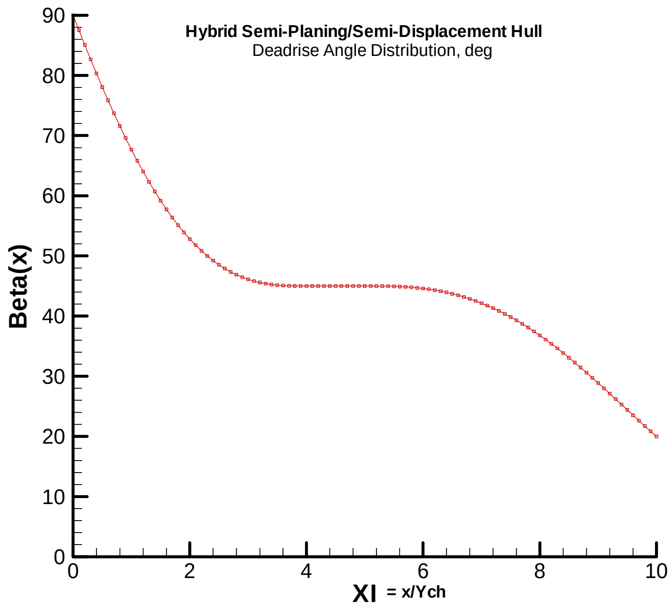

Fig 3: Deadrise Angle Distribution in x

Note particularly from Figure 1 that, unlike planing craft, the trim is zero consistent with displacement vessel attitude. This allows the application of a surface (or wave) piercing stem, as exhibited by Figure 1.

Xcw indicated on Figure 2 is the chine wetting point, where the jet-head has risen up the hull sides to intersect the chine. The jet-head offset is shown on Figure 2 and lies inside (under) the chine until the intersection at *Xcw*, after which the jet-head and the chine are coincident. The implication of Figure 2 is that the hard chine is not involved with the hull surface flow until it wets at 75% of the length aft. The forebody can therefore be viewed as chineless, with the forward lines like those of a conventional fine-hulled displacement ship.

The rapid reduction in deadrise angle, as indicated on Figure 1, and plotted specifically on Figure 3, is responsible for the rapid rise of the jet-head toward chine wetting seen in Figure 3.

Table I summarizes the calm-water analysis.

Table I: Analysis Summary – Prototype Hybrid SemiHull, Calm Water Performance

Hull length/Ych	10
Vessel operating draft/Ych	.6
Vessel operating trim, deg	0
Xcg/Ych forward of transom	2.763
Vessel speed, knots	50
Design Froude number	1.064

Hydrostatic lift at operating draft, $\dfrac{\ell_b}{\frac{1}{2}\rho U^2 Y_{ch}^2}$	.7780
Wave lift	.4638
Total dynamic lift	.4990
Total lift (.7780 + .4990)	1.277
Viscous drag, $\dfrac{\ell_b}{\frac{1}{2}\rho U^2 Y_{ch}^2}$	.06160
Induced, spray, and transom drag	.01493
Wave drag due to waterplane wave-making vortices	.05019
Wave drag due to centerplane wave-making sources	.01164
Total Drag (.06160 + .01493 + .05019 + .01164)	.13836
Lift/Drag Ratio (1.277 / .13836)	9.22

Comparison Case

It is useful to explore the question of whether the Hybrid Semihull form, which develops dynamic lift, and also a dynamic lift-related component of wave resistance, has the potential to compete with the non-lifting displacement hull, which develops only the one displacement component of wave resistance.

The codes developed for this research were used to re-perform the preceding analysis on a hull with lines more characteristic of a conventional displacement ship form. For this the doubly parabolic mathematical hull form was used. The wave resistance of this form has been well studied. The body plan is Figure 13. This parabolic hull was set with the same speed, length, and beam as the hybrid. However, in order to achieve the same weight a draft adjustment from T/L = .06 to T/L = .0808 was required. The trim was set to zero, giving an Xcg/L = .5 with the fore-and-aft symmetry.

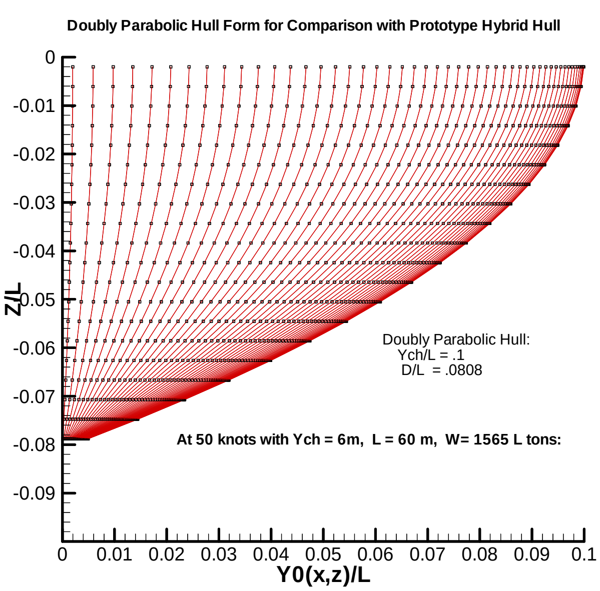

Fig 4: Body Plan of Doubly Parabolic Hull

Table II gives the comparison summary.

Table II – Resistance Comparison - Parabolic and Hybrid SemiHulls

	Hybrid SemiHull	Parabolic Hull
Total Lift Coefficient	1.277	1.277
Viscous Drag Coefficient	.06106	.06606
Wave Drag Coefficient	.06183	.1327
Total Drag Coefficient	.13836	.19876
Lift/Drag Ratio	9.22	6.425

Note that the major reason for the different total resistances is the much higher wave resistance of the Parabolic hull. This is due to the deeper draft of the Parabolic hull as needed to make up for the dynamic lift component of the Semi-hull.

2. Catamaran wet-deck slamming (years 2 and 3)

A) Flat Wet-Deck Case

The US Navy LCS-X, Figure 5, is a good example of a high-speed flat wet deck ship.

Office of Naval Research high speed, experimental aluminum catamaran “X-Craft”. LOA: 262 ft. long DISP: 950 tonnes(LS) Speed: 50 kts, 40kts in Sea State 4

Fig 5

The objective of the analysis here was prediction of the slamming pressure and resultant loads on the wet-deck flat under-surfaces, first, for better physical understanding of the hydrodynamic processes, but also for the ultimate practical purposes of structural design and analysis.

Two separate but coupled analyses were required to support this objective:

A) *The wet deck impact with the water surface*. Catamaran wet-deck slamming with forward speed is truly a planing/slamming process, in the sense of the pioneering (calm water) sea-plane landing-impact hydrodynamics of vonKarman' and Wagner back in the 1920's and 1930's (vonKarman'(1929), Wagner(1932)). The water entry is a dry entry, with the wet-deck surface falling with forward speed from above the water surface, like the fuselage pontoon of the sea plane landing in ocean waves. There are several differences however. Most notably, the seaplane pontoon is low-aspect-ratio, where the dominant flow perturbation is transverse, and low-aspect-ratio theory was used for that analysis. Similarly, low-aspect-ratio theory is the universal approximation applied to planing boat hydrodynamics, e.g., Tulin (1957). High-aspect-ratio theory, rather than low-aspect-ratio theory, applies, however, to flat wet-deck slamming, even though it is an unsteady planing process. This is, again, because of the blockage of the transverse flow by the demi-hulls, as discussed above. The analysis follows the unsteady hydrofoil hydrodynamics documented in Newman(1976), but extends that fully submerged theory to the case of unsteady high-aspect-ratio planning.

B) *Prediction of the relative displacements and velocities of the ship and waves that lead to wet deck slamming*. Ship motion theory, in any of various forms, is available for providing the driving conditions for slamming. After inception, the slam hydrodynamics affects the ship motions and ensuing flexural dynamic response, and that is allowed for here approximately by a "Structural Rigidity Factor" (SRF).

The hydrodynamic solution model for the flat wet-deck case is depicted on Fig 6.

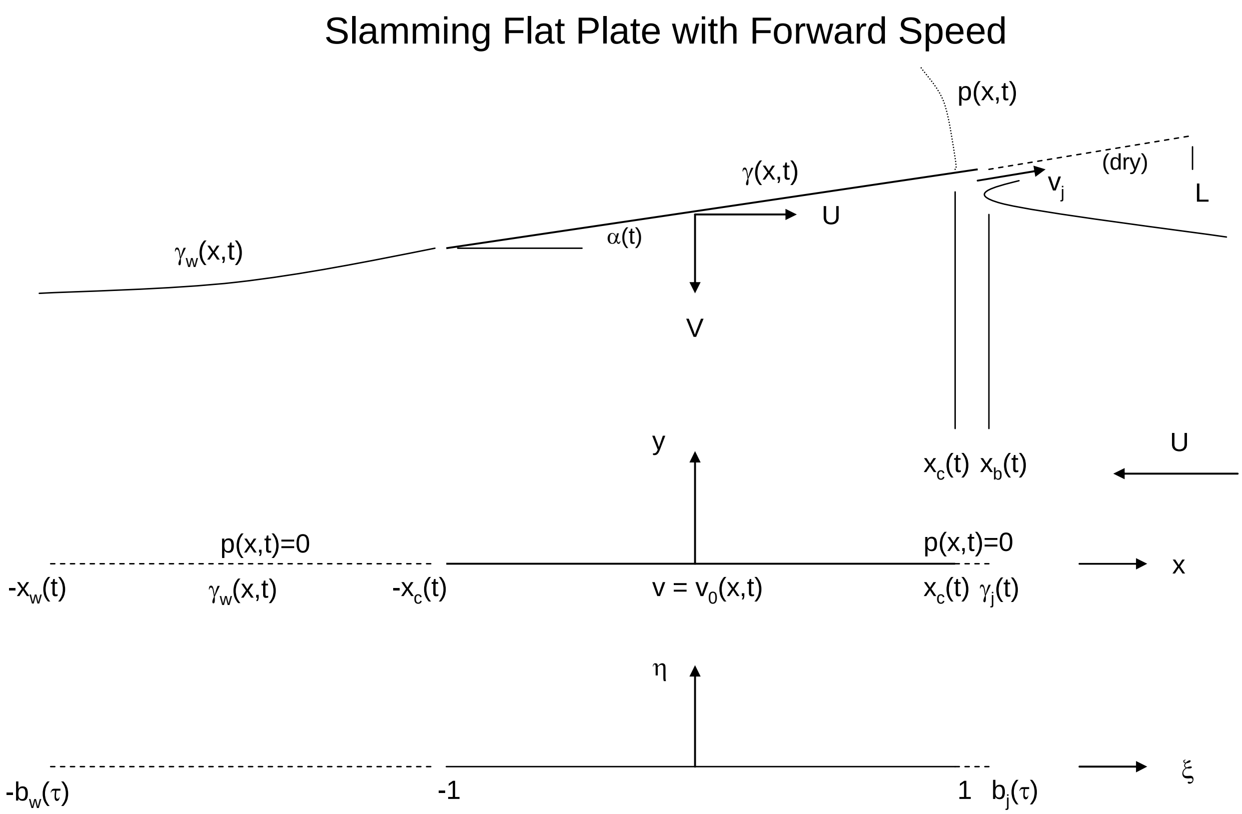

Fig. 6 (a) Slamming Flat Plate with Forward Speed U; (b) Identification of variables and linearization to the y axis; (c) Non-dimensionalization on $x_c(t)$.

Figures 7 and 8 show the predicted slamming domain based on relative displacements of the sea surface, approximated as a regular head wave. Fig 7 is the displacement subspace of interest and figure 8 the relative velocity subspace.

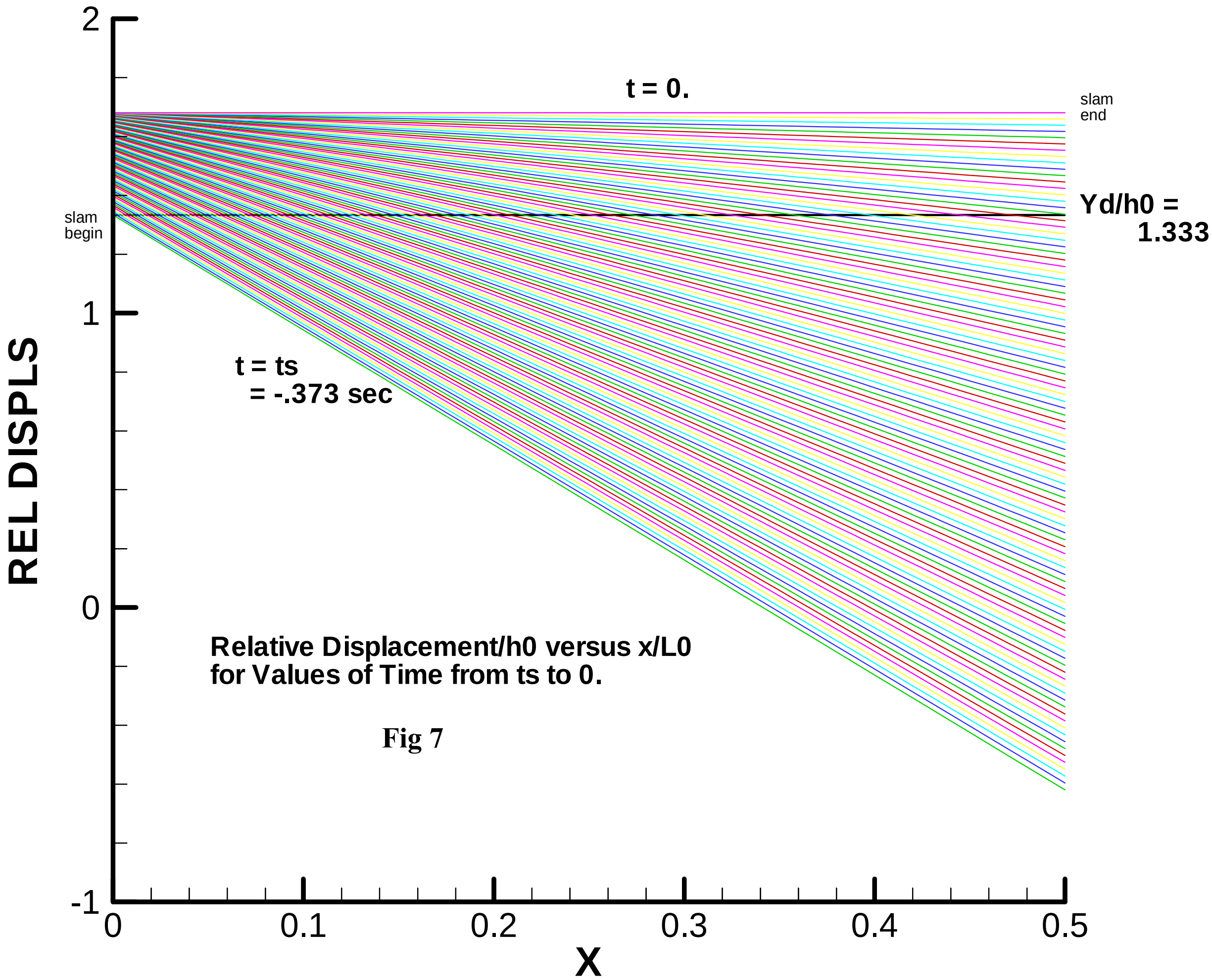

Fig 7

Here, for the test case selected, slamming occurs when the relative displacement and velocity are both positive ; relative displacement is the distance from the calm waterline to the wet deck less the predicted difference in the wave height and vertical motion displacement versus time and the distance forward from midship. The two figures are plots of relative displacement and velocity versus x for values of relative time.

t_s is the time for slam commencement and the vessel bow is high with relative movement down. Slam duration is therefore from t =–t_s to t = 0. This space is above the dashed black line on Figure 7 is the space of the slam, in which the relative velocity is downward.

As an example case the catamaran defined in Table III was analyzed.

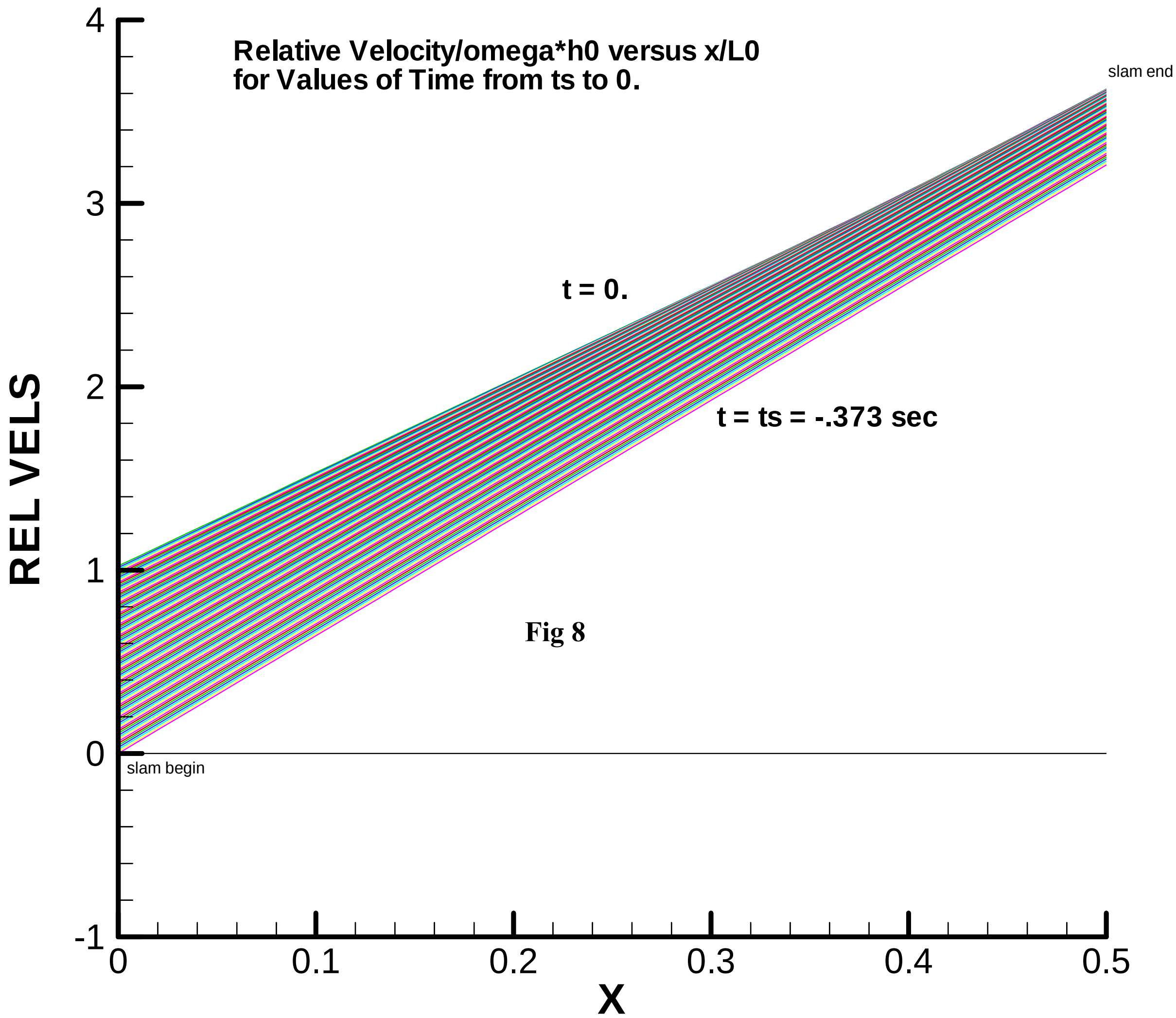

Fig 8

Table III - Example Application

U = ship speed = *50* knots

L_0 = half-ship length = *250* ft

T = draft = *9* ft

B = total beam of both demihulls = *30* ft

H_{wd} = depth keel to wet deck = *17* ft

W = wet-deck beam =*50* ft

λ = wave length =*500* ft

h_0 = wave amplitude = 6 ft

The wave length, λ, was selected as follows. The frequency of encounter of the vessel, allowing for the 50 knot forward speed was 1.7 rad/sec. It was concluded early in the work that, for maximum frequency of slamming, the natural frequency in heave/pitch should be lower than the frequency of encounter so that the vessel would be running at supercritical frequency ratio. From linear vibration theory this produces a response with the vessel oscillating out-of-phase with the waves, with the result being maximum relative displacement and velocity.

The predicted bow motion input is shown on Figure 9 corresponding to one cycle of the slam. The negative slamming time from – t_s to 0 has been shifted for convenience to 0 to t_s (Figs 7 and 8).

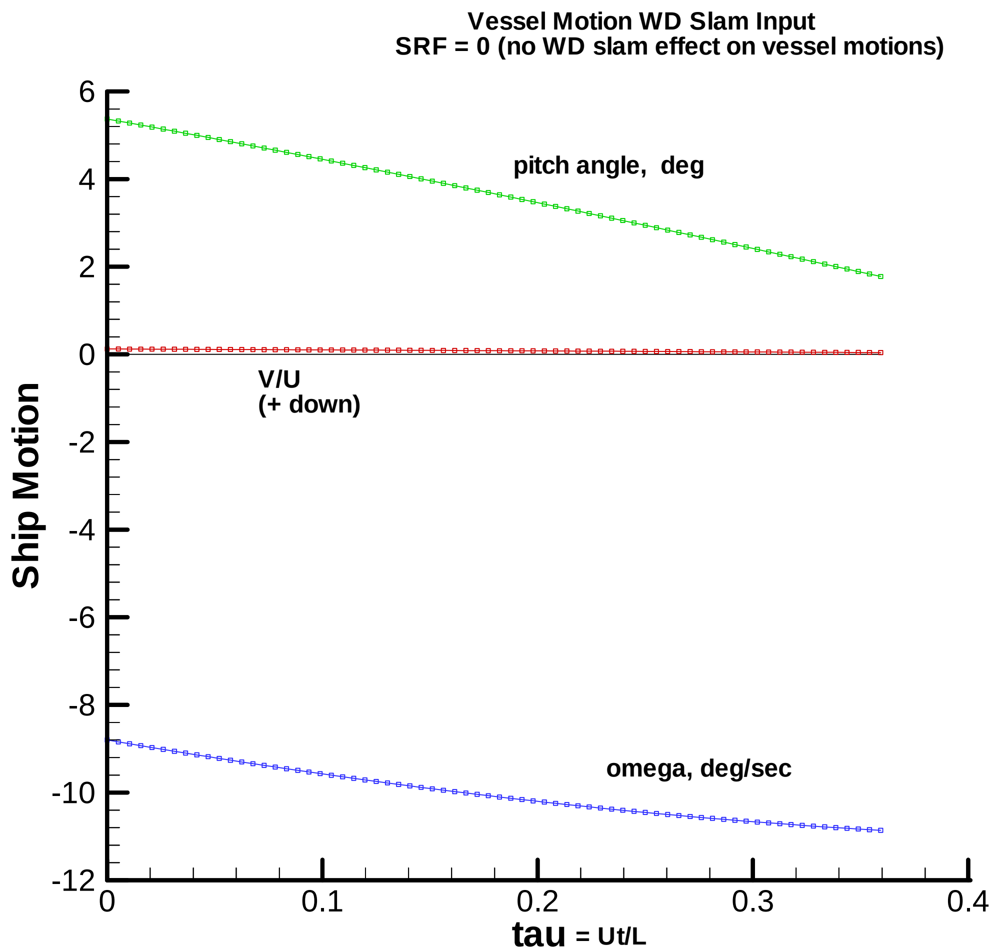

Fig 9: Vessel Bow Motions (x > 0) for Slam Input

The increasing negative angular velocity is the dominant slam motion, corresponding to the bow driving down.

The rigid body motion assumed in the analysis to this point produces slam forces that are impossibly large. As at result a "Structural Rigidity Factor (SRF) was included to allow for wet deck slamming not fully accelerating the total hull mass and mass moment of inertia. This is due to mass in the wet-deck and serial structural flexibility in the connections. SRF = 0 implies a fully flexible wet-deck structural connection, such that the hull inertial effects in absorbing shock loading are zero, and the wet-deck structure takes the entire slam loading locally. SRF = 1 implies a rigid connection of the wet-deck to the hull so that the full vessel mass is effective in absorbing the wet-deck impact and limiting the impact acceleration.

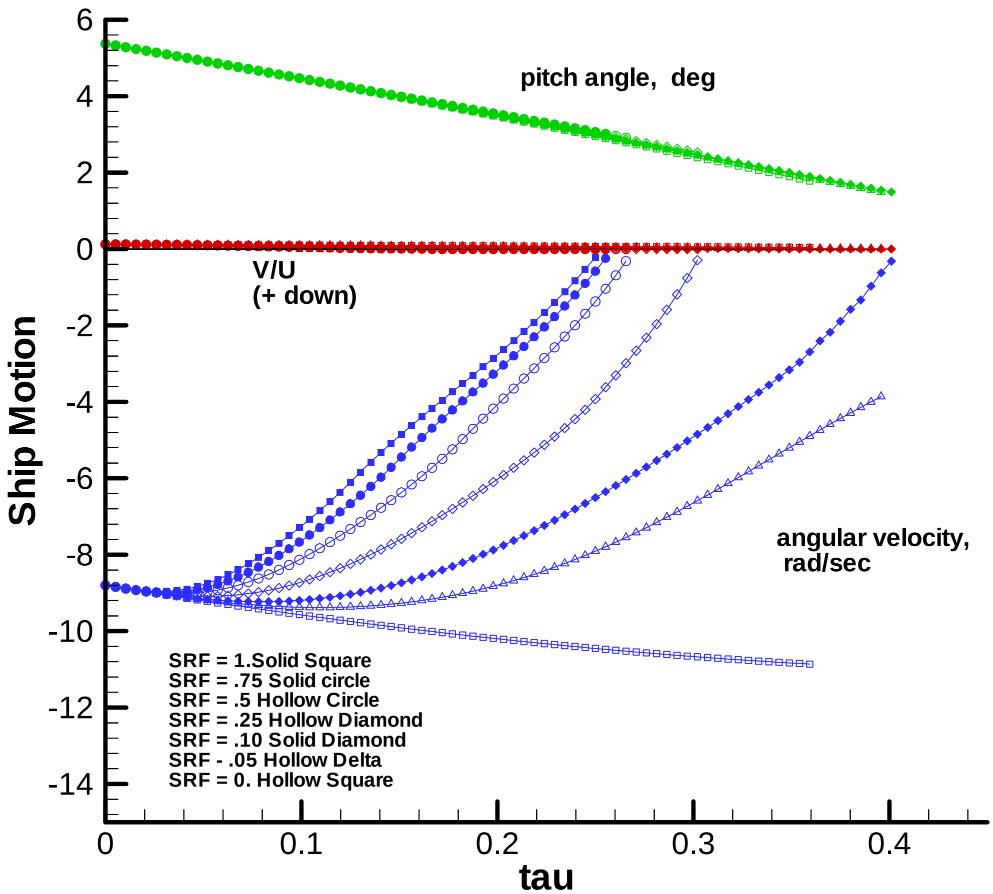

Fig 10: Vessel net motions between the SRF extremes ($0 \leq SRF \leq 1.$)

While no effort was made to perform the structural analysis needed to quantify the SRF for any particular case, calculation of the effects on slamming over a range of SRF were evaluated for the example ship. The result of SRF in the slamming motion as an expansion of Fig 9 are superimposed on Fig 10. Here the effect on the Fig 10 motions for SRF varying incrementally between 0 and 1 are shown.

It is clear, again, from Figure 10 that the only significant effect of the hull inertia is on the bow downward angular velocity. It is also clear from Figure 10 that the slam terminates either because the jet-head runs off the stem of the bow (SRF = 0. and .05), or because the hull angular velocity is reduced to zero by the hull inertia before the jet-head reaches the stem (SRF = .1 to 1.).

Figure 11 shows the corresponding total forces and moments for the SRF range.

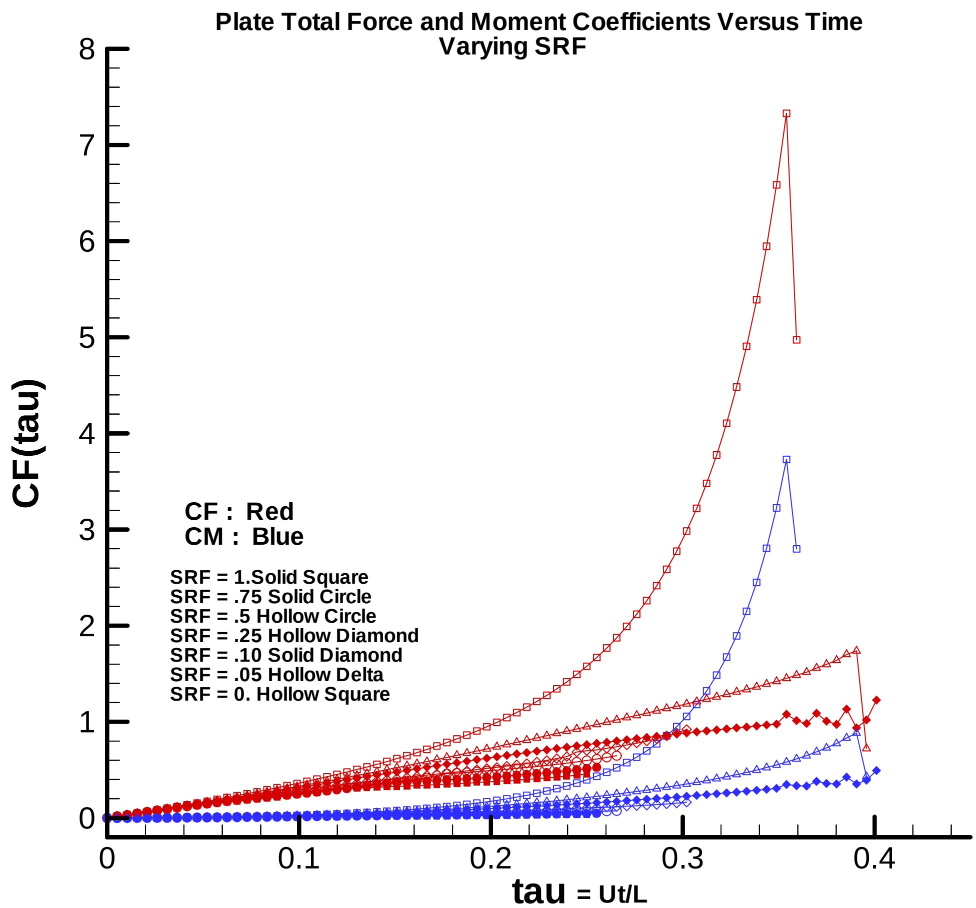

Fig 11: Total Forces and Moment Coefficients Versus τ for Values of SRF

The effects of the decaying hull angular velocity on the force and moment coefficients is similarly as dramatic as on the pressure coefficients. A force coefficient of around 1. on Figure 11 implies a total impact force of a little over 10% of that predicted for *SRF* = 0 (but still a very large value in excess of 20,000 tons (10 times the vessel weight)).

Figure 11 shows slight oscillation sensitivity on approaching the bow for *SRF* = .1. From Fig 11, this *SRF* appears to be close to the limit of the transition in the two modes of slam termination: bow run-off versus angular velocity nullification. It is considered not have any serious implication regarding the physics captured by the hydrodynamic model.

B) Non-flat Wet-Deck Case

It appears to be necessary that the flat wet-deck be avoided because of the wet-deck slamming intensity as demonstrated in the last sub-section A relatively successful bow design has been the monohull center bow of the Incat wave-piercing catamaran design, Figure 12. Although bthese vessels are still reported to suffer structural degradation in the turn into the demihull tangents.

The year 3 work of the subject project investigated various hull section shapes in search of improvements.

Fig 12: Incat Catamaran with Wave Piercing Bow.

The best shape investigated was the “inverted-V” section, depicted on Figure 13.

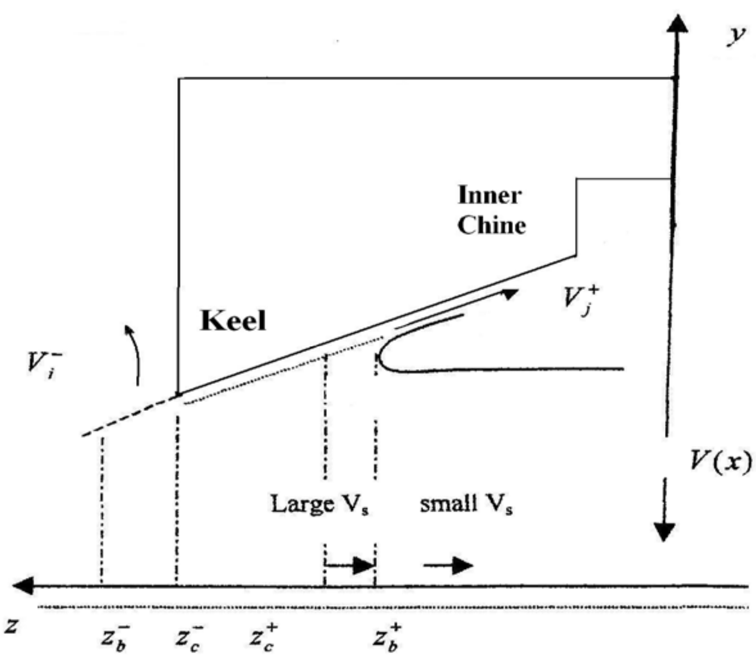

Fig 13: Inverse-V (half) Section and Flow.

This section is that applied successfully in the Hickman Sea Sled monohull concept some years ago. Unlike with the flat-wet-deck model, where the impact flow is taken to be entirely axial, the flow here is taken to be entirely transverse, consistent with Slender Body Theory, (Vorus, 1996). Its distinguishing flow feature is that. With the keels outboard and the chines inboard, the slam flow runs from outside to inside. This closure of the jets toward the chines and toward each other, results in pressure cancellation and reduced slam intensities during impact.

Prediction have been made with a code "V-Inverse," developed initially in another project concerned with steady planing, and adapted for the center bow of the catamaran impact case. In this regard, one physical approximation has been retained from the steady planing model that does not apply: Fig 13 shows a flow outward at the keels. This flow would be blocked by the demi-hull side walls for the catamaran wet-deck adaptation. This error was investigated and the outer keel-wetted flow is small compared to the inner jet head flow. The boundary condition was not altered, but would easily be should this work be continued.

Relative to the flat wet-deck work, all was taken as the same for the inverse-V model except the bow center hull, i.e., Figures 7 and 8 were retained from the flat wet-deck work of the last section. Pressure and force predictions are therefore comparable to the flat wet-deck case.

Figure 14 shows the predicted pressure distributions in the cross-sections at x/(L/2) = 1. as the slam progresses in time. The jet heads are progressing inward from the keels (Fig 13).

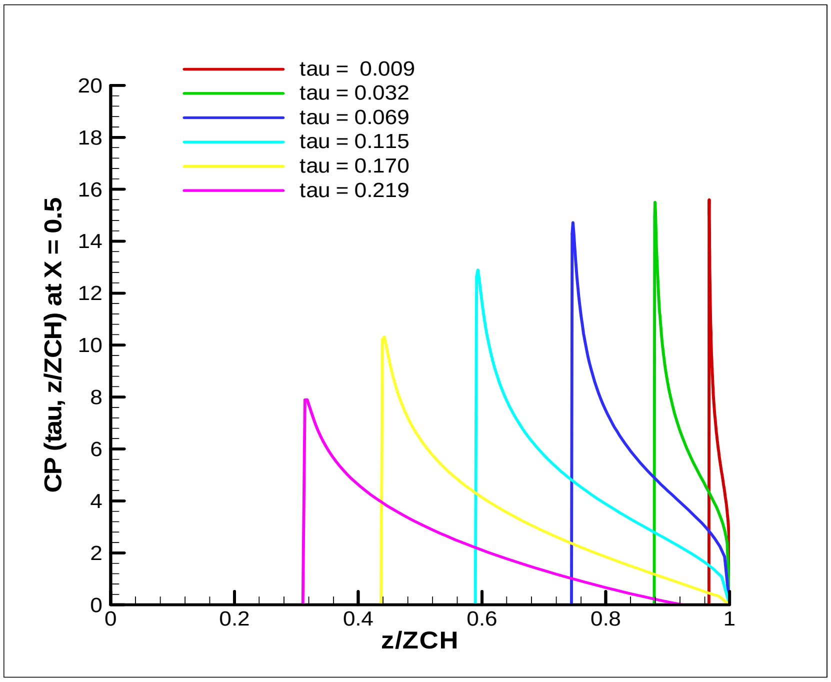

Fig 14: Cross-sectional Pressure Distributions at the Bow

Figure 15 is a corresponding pressure plot for the flat wet-deck case, but at all x-coordinates. One implication of Figures 14 and 15 is that the slam pressure is much less intense with the inverse-V wet deck. The flat wet-deck pressures are higher by a factor in excess of 4-to-1. Further, the slam pressure with the flat wet-deck is constant across the wet-deck beam at any x and τ. The slam forces are thereby implied to be much higher with the flat wet-deck.

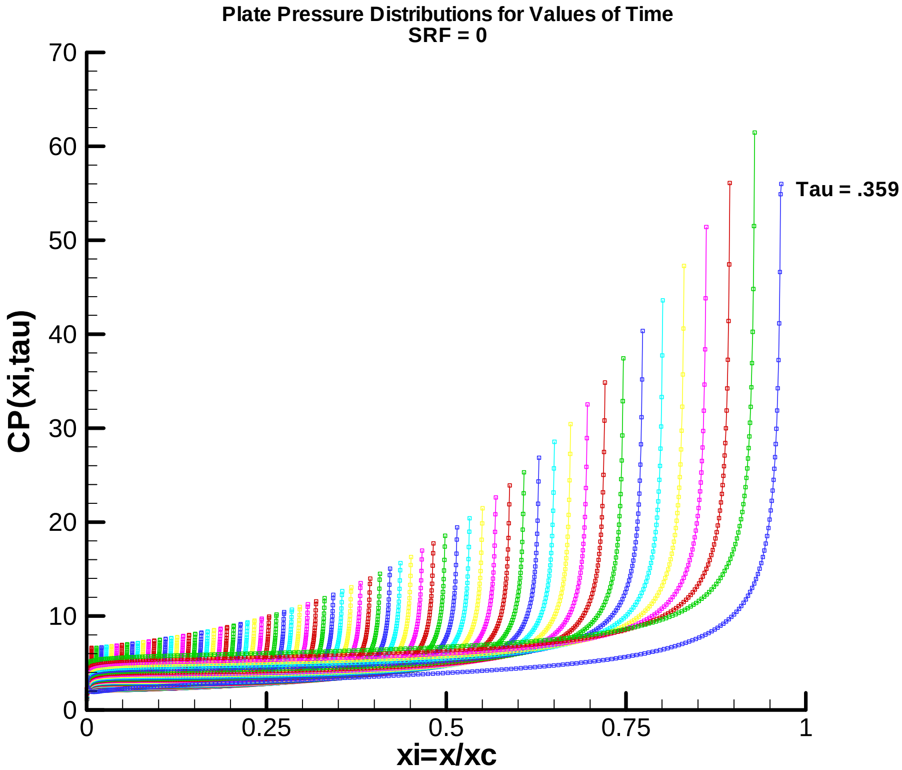

Fig 15: Flat Wet-Deck Pressure Distribution for SRF = 0.

<u>CONCLUSIONS</u> (present substantiated findings; discuss their implications and present author's opinion)

1) It is the author's opinion, based on the year 1 analysis, that an alternative to multi-hulls for reducing high speed vessel wave resistance is monohulls developing some fraction of the total required lift from dynamics (as in planing).

2) It has been confirmed that wet-deck slamming of flat wet-deck ships is dangerous to ship structural integrity and that flat wet-decks should be avoided in design.

3) It is the author's opinion that a good alternative to flat wet decks is an inverse-V cross-section where significant slam pressure cancellation has been predicted to occur.

<u>RECOMMENDATIONS</u> (suggest a course of action)

The conclusions above are considered to be valid, but they are clearly preliminary. The problems studies are very important to high-speed ships and are deserving of further development. Continuation of the work in both areas is recommended.

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(see appendices for full reference lists)

<u>BIBLIOGRAPHY</u> (list additional sources of information not cited in the text of report)

<u>LIST OF SYMBOLS, ABBREVIATIONS, and ACRONYMS</u> (explain meaning. Required if there are more than 5 not readily recognized as standard)

<u>GLOSSARY</u> (defines and explains unfamiliar terms)

<u>INDEX</u> (lists major topics alphabetically. Not required in reports of fewer than 50 pages)

<u>DISTRIBUTION LIST</u> (give permanent record of initial distribution of report)

Appendix A – Monthly Status Reports

A compilation of all monthly status reports has been inserted here.

SDT_Quarterly
Reports.pdf

Appendix B – ONR Yearly Reports

A compilation of all ONR Yearly reports has been inserted here.

Appendix B - ONR
Yearly Reports.pdf

Appendix C – MS Degree Documents – Inverse V Tools

Attachment C -
Inverse V Tools.pdf